AIntelia

Investigating the conductivity of silk and wool textiles by applying AgNPs and their performance analysis

Md Safuan Islam[1], Dicle ÖZDEMİR KÜÇÜKÇAPRAZ[2]
[1]Süleyman Demirel University, Isparta, Turkey, te.safuan@gmail.com, 0000-0002-8711-6297
[2]Süleyman Demirel University, Isparta, Turkey, diclekucukcapraz@sdu.edu.tr, 0000-0003-0209-8323

Conductive textiles play an important role in modern textile science as scientists are trying to integrate electronic devices into clothing for various purposes such as transmitting, tracking, and controlling movements. For this reason, researchers are trying to improve the conductivity of fabrics or yarns by using various materials and methods. In this study, the authors optimized conductive ink solution which is based on silver nanoparticles (AgNPs) known as electrically conductive which is applicable to traditional silk and wool textile products by printing and dyeing methods. With this application, the authors offered an innovative approach to the production of conductive textile surfaces. Several tests have been done to find out the change of conductivity and if those materials are applicable for our daily life usage. After applying AgNPs ink solution, the conductivity of silk (34.78 S/cm) is much higher than wool (25.28 S/cm) but after the color-fastness to rubbing test, wool's (2.12 S/cm) conductivity is much higher than silk (1.01 S/cm). On the other hand, after the wash fastness test, the conductivity of wool decreased (5.43 S/cm). So, the authors have found that the conductive wool yarn is much more stable than silk yarn or fabric for daily life application

Keywords: *Conductive ink, Conductive textiles, Dyeing, Printing.* .

© 2022 Published by *AIntelia*

1. Introduction

Textile products have grown in different directions in recent years in terms of comfort and functionality [1]. Conductive textiles play an important role in the modern era of textile science. Today, scientists are trying to integrate electronic devices into textiles for various purposes such as sensing, energy harvest, thermo-electricity, military & defense, building & construction, automotive, clothing, and medical [2]. For this reason, researchers are trying to improve the conductivity of fabric or yarn by using various materials and methods [3]. One of the ways to produce textile products with high added value is to apply innovative approaches to produce products.

Conductive ink is very important for electronic textiles which contain electricity to produce conductive patterns. It is consist of conductive materials, solvents, and additives [4]. It plays a major role to determine the electrical properties of the final products.

Researchers have used various methods such as sputtering, electroless coating, spray coating, plasma treatment, vacuum metallization, chemical vapor deposition to deposit conductive materials on the yarn or fabric surface, and methods such as screen printing, rotary printing, and inkjet printing for printing processes [5-6]. But dyeing and embroidery are the latest processes to develop conductive textiles [7]. But in this study, not only will the conductive ink be printed with the screen printing method, but also the yarn containing the conductive ink will be dyed to produce conductive yarns. Therefore, the dyeing method will be used to produce conductive yarn. Because these processes are easy, low cost, and more efficient. With this method, it is possible to deposit conductive particles uniformly. On the other hand, the surface of the fabric will be made conductive by using the printing method.
Until this time, researchers have used conductive materials such as iron, copper, silver, carbon, gold, aluminum, and graphene to improve electrical conductivity in textile materials [8]. Among these, silver is the

best choice for use as a conductive material, because silver has shown high electrical conductivity, is non-toxic and non-corrosive, and stands out with its properties such as non-reactivity in contact with the skin [9]. At the same time, silver is the best option because of its antimicrobial properties [10]. But the only problem with silver is that its price is slightly higher than other conductive materials. On the other hand, among materials such as iron, copper, carbon, gold, aluminum, and graphene, the electrical conductivity of carbon nanotubes and graphene is much higher than silver [11]. Although carbon nanotubes and graphene have higher electrical conductivity, they are toxic and corrosive, causing harm to both humans and the environment [12]. Therefore, in this research work, Nano-silver powder as conductive ink particles is primarily preferred, regardless of its cost, especially in products in contact with the human body.

The most important aim of our study is to examine and evaluate the effects of physical conditions on conductivity. In addition, increasing the performance properties of conductive textile surfaces in terms of the user is one of the secondary important goals of this study. For this purpose, various tests such as conductivity, color-fastness to rubbing, wash fastness, and durability have been carried out in order to understand their properties and conductivity, and a method of integrating conductive ink into the yarn has been developed in line with the results.

Before being put on the market, the change in the properties of conductive textile products and their effects need to be studied in detail. The aim of this research is to produce low-cost conductive yarns or fabrics using an easy method for application in our daily life.

2. Materials and methods

Materials

For the purpose of this study, silver nanoparticles (AgNPs) within particle size 18 nm are used as a conductive material because the more the particles size are smaller the more they will mix up with the solution easily and can be attached to the surface of the substrate [13]. Hydroxyethyl-cellulose solution 0.5%, Water, Diethylene glycol, Triethanolamine, Hyperdispersant (Solsperse 20000), Polyvinylpyrrolidone (PVP) solution 5% are used as the chemicals for producing the ink solution.

Yarn or Fabric-based substrates for producing electronic surfaces are more suitable than other substrates. For this reason, 100% wool yarn and 100% silk fabric have been used for this experiment. As silk yarn is very finer in diameter, so it is not possible to hold the ink particles on its surface. That's why silk fabric is used instead of silk yarn.

Methods

Screen printing [14] and yarn dyeing [15] are the main approaches for the fabrication of conductive ink into textile substrates for producing a conductive surface that has been used in this study.

Preparation of ink solution

The solution is a combination of various chemicals and metal silver nanoparticles. Hydroxyethyl-cellulose (HEC) 0.5%, water, Diethylene glycol, Triethanolamine, Hyperdispersant (Solsperse 20000), Polyvinylpyrrolidone (PVP) 5% chemical are used to prepare the stock solutions. The solution was run for 3 hours at 1000 rpm for a homogeneous mixture within a magnetic stirrer. Then 8g AgNPs were added to 50 ml of the stock solutions. It was run for another 2 hours at 1000 rpm at 30˚C with a magnetic stirrer. After that, the solution was conditioning for 24 hours at 4˚C in the refrigerator.

Printing process

In the screen printing process, first, the template is placed on the determining part of the fabric, fixed and the printing paste is poured on the upper edge of the template. The printing process is carried out by pushing the printing paste from the pores of the template to the fabric surface by the downward movement of the doctor from the top of the template. In this way, printing paste is transferred to the fabric with 1 passage of the doctor and the printing process is performed [14], [16].

Dyeing process

Before applying the solution for dyeing, the solution was run for 1 hour at 1000 rpm at 30˚C. Then each sample was immersed in the solution and run for 5 minutes at 500 rpm at 30˚C. In this way, the yarns were dyed to impose the conductivity of the substrate surface [15].

Analysis & Data Collection methods

For the case studies, identification of the yarns, count measurement of the yarn or fabrics, EPcm and PPcm of the fabric, GSM of the fabric, morphology analysis, absorbency test, pH measurement, Viscosity measurement, Electrical conductivity test, Colorfastness to rubbing (Dry & Wet) test, wash fastness test have been done. Tests were performed following the test method provided by ASTM and AATCC Standards.

Identification of the yarn by a chemical test method

The chemical analysis procedure was used to identify the yarn. For this test, AATCC TM 20A-2002 [17] was followed. In order to measure the chemical composition of the yarn, the concentration of 5% of Sodium hypochlorite (NaOCl) at the temperature of 20˚C was taken in a beaker. Then each sample was immersed in the chemical for 20 minutes.

Count measurement

ASTM D 1907-01 IS 1315-1977 [18] method is followed for measuring the count. At first, the weight of the 1 g yarn was taken and its length was measured in meters. Then count is calculated in the indirect system. The denier count is weight in grams of 9000 meters of yarn.

$$\text{Denier count (D)} = \frac{\text{Weight of yarn in grams} \times 9000\ \text{m}}{1\text{gm} \times \text{Length of yarn in meters}}$$

Ends per centimeter (EPcm) and Picks per centimeter (PPcm) measurement

In order to measure EPcm and PPcm, a 1 sq. cm sample is taken. The number of yarns in both warp and weft directions is counted. The number of warp yarns per sq. cm is EPcm and the number of weft yarns per sq. cm is PPcm.

Gram per square meter (GSM) test

Fabric is cut by GSM Cutter and the cut piece is measured in electric balance. ASTM D 3776 [19] method is used to calculate GSM.

Morphology analysis

The morphological value of the wool yarn and silk fabric was examined by using 360 SUPER HD MICROSCOPE making the image size 200X.
Brand: Discovery Channel
Model: 8001
Origin: Hong Kong

Absorbency test

Absorbency is an important factor to understand solution take-up percentage. The wettability or absorbency of textile fabrics or yarns can be determined by AATCC 197 [20] method. In this standard, the bottom of the specimen comes into contact with water. Then, the wicking distance by specified time intervals is recorded. The higher the wicking distance at the same interval, the better the fabric is in wicking.

pH measurement

Machine used - Hi 2211 ph/orp meter
The temperature was 22˚C and humidity was 60% and the chemical was cooled after preparation. The probe was immersed in the sample and result will be shown on the LCD display.

Viscosity measurement

The capillary viscometer (Ostwald viscometer) method measures the time taken for a defined volume of fluid to flow through a U-shaped capillary tube of known diameter and length. for the measuring, the viscosity of any solution following equation has been used [21],

$$\frac{\mu_1}{\mu_2} = \frac{\rho_1 t_1}{\rho_2 t_2} \tag{1}$$

Here, μ_1 is the viscosity of the tasted liquid, μ_2 is the viscosity of the water (0.89 cp)

ρ_1 is the density of the tasted liquid, ρ_2 is the density of the water (1 at 25˚C)

t_1 timing of runout of the tasted liquid, t_2 timing of runout of the water (18.2 s)

Electrical conductivity test

The two probe method was used to test the resistance of yarns or fabrics. Samples were air-conditioned and measurement was carried out at 50% RH, 24°C. Resistance of samples was measured by using Clamp multimeter UT201 at different distances between the ends of the specimen. The electrical conductivity of samples was calculated by the formulas mentioned below [22],

$$\rho = R_s \times \frac{A}{l} \tag{2}$$

$$\sigma = \frac{1}{\rho} \tag{3}$$

Wher, ρ is the resistivity of the sample in ohm/cm, R_s is the sheet resistance (Ω), A is the sample thickness (cm), l is the sample length (cm), and σ is the conductivity of the sample (S/cm).

Colorfastness to rubbing test (dry & wet)

AATCC TM 8-2001 [23] method was used for this test. A colored test specimen is rubbed with a white crock test cloth under con rolled conditions. Color transferred to the white test cloth is assessed by comparison with the Gray Scale for Staining or the Chromatic Transference Scale and a grade is assigned.

Washing fastness test

AATCC TM 6-2001 [24] method was used for this test. Those washing tests are done to determine the frequent withstand of laundering. Samples are tested under appropriate conditions with a detergent solution. The color change is obtained in a short time.

3. Result and discussion

Identification of yarn

The chemical identification process is used to identify the yarn type. This is the easiest way to identify the yarn. The obtained result is given in table 1.

Table 1. *Yarn identification*

Wool	Concentration 5% Temperature 20˚C Time 20 minutes	Sodium hypochlorite (NaOCl)	Soluble
Silk	Concentration 5% Temperature 20˚C Time 20 minutes	Sodium hypochlorite (NaOCl)	Soluble

By using a 5% concentration of Sodium hypochlorite (NaOCl) if samples are soluble in the solution, then those samples are either wool or silk.

Count (denier)

The indirect (denier) count measurement system is used to measure the count of the yarn or fabric. For this test bleached and washed samples are being used and the result is shown in table 2.

Table 2. *Count measurement*

Sample name	Count (Denier)	Condition
Wool yarn	94 D	Bleached & washed
Silk fabric	Warp- 18 D Weft – 43 D	Bleached & washed

The result shows that wool yarn's count is higher and thicker in diameter. On the other hand, silk yarn's count is relatively lower and thinner in diameter.

EPcm and PPcm

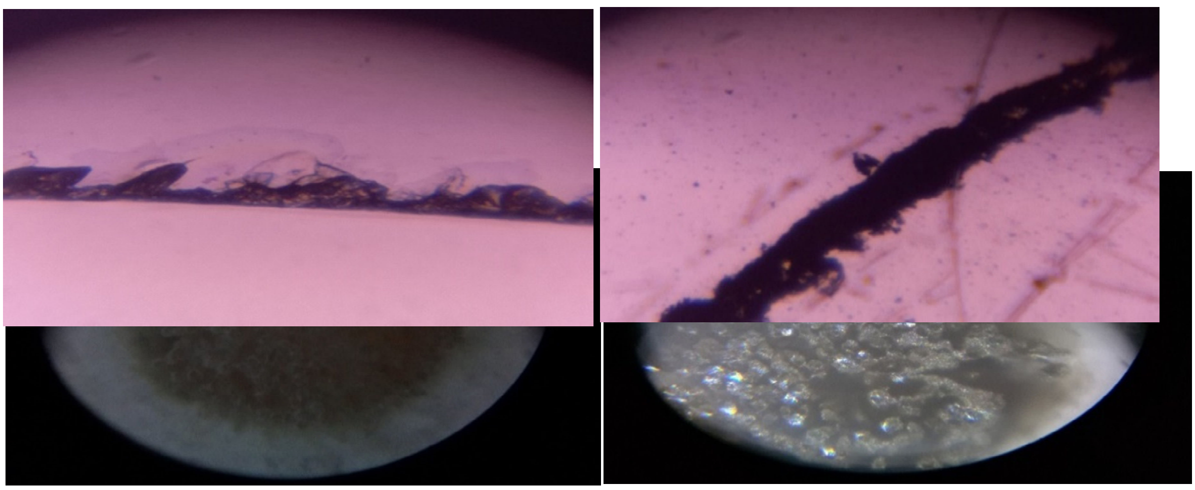
The calculated EPcm and PPcm of silk fabric is 32X44 and plain weave.

GSM

In this work, GSM is measured as cm^2. So the measured GSCM of the silk fabric is 0.26 g/cm^2.

Morphology analysis

The microscopic view of the wool and silk yarn has been observed both on the longitudinal and cross-sectional side before applying the conductive ink solution and after the applying conductive ink solution.



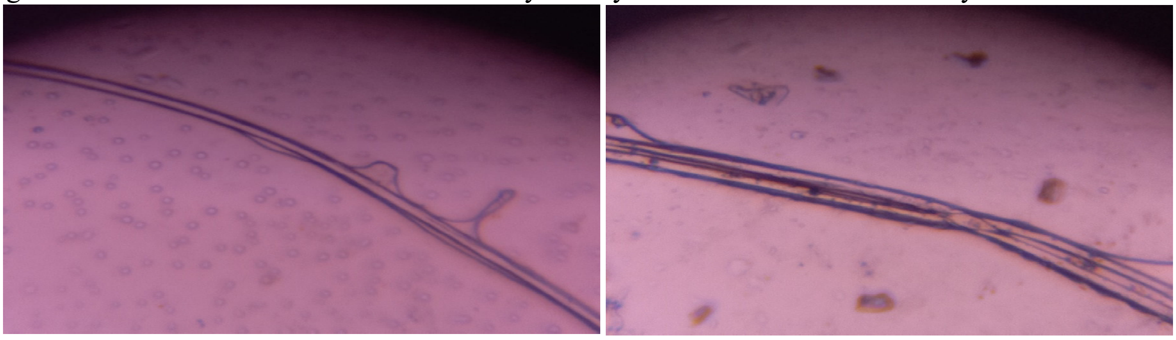
(a) (b)

Figure 1. *Longitudinal view of wool fiber before (a) and after (b) dyeing in AgNPs solution.*

(a) (b)

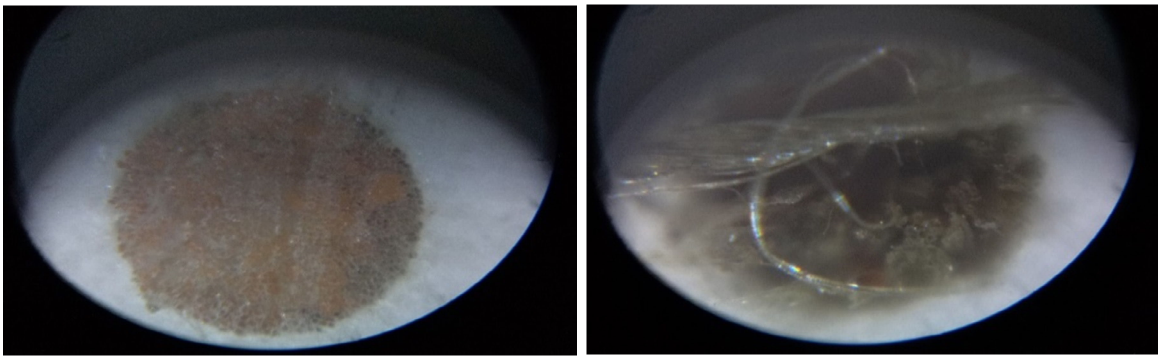
Figure 2. *Cross-sectional view of wool yarn before (a) and after (b) dyeing in AgNPs solution.*

The bonding between conductive ink solution and the wool yarn can be seen in Figures 1 and 2. The wool fiber is composed of a protein chain of amino acids. Most amino acids have the general formula H2N.CHR.COOH. R is a side chain with different compounds [25] that can create a strong bond with Ag particles. H in amino acid also can create a strong bond with Ag particles. As wool's diameter is relatively high so absorbs more ink solutions. That's why wool yarn shows stable conductivity.



(a) (b)

Figure 3. *Longitudinal view of silk fiber before (a) and after (b) dyeing in AgNPs solution.*



(a) (b)

Figure 4. *Cross-sectional view of silk yarn before (a) and after (b) dyeing in AgNPs solution.*

The bonding between conductive ink solution and the silk yarn can be seen in Figures 3 and 4. The silk fiber is consist of two types of proteins; sericin and fibroin. "Fibroin mainly composites of the amino acids Gly-Ser-Gly-Ala-Gly-Ala and forms beta-pleated sheets, β-keratin". R = H, glycine; R = CH3, alanine; R = CH2OH, serine [26] which creates a more strong bond with Ag particles and makes the silk yarn more conductive. But the diameter of the silk is relatively low so it will absorb less ink solution than wool yarn and its conductivity is less stable than wool yarn.

Absorbency

Absorbency is a very important factor for dyeing because it calculates how much solution will be transferred from the dye bath to the materials. It will also affect the conductivity.

Absorbancy of the pure yarn

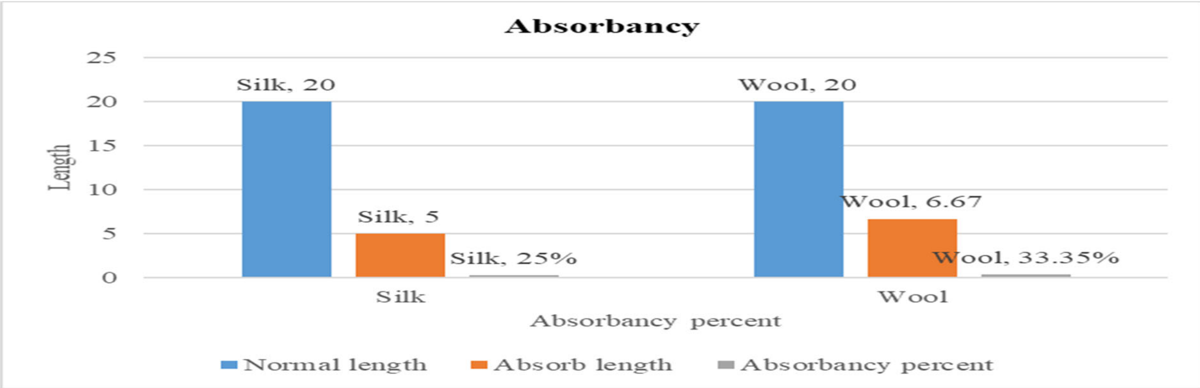


Figure 5. *Absorbancy of the pure silk and wool yarn*

Figure 5 shows that the solution takes up percentage is very important for making the substrate conductive. The more the take-up percentage, the more it will be conductive in nature. So, the conductivity of wool yarn will be more than silk yarn as its taken-up percentage is higher than silk.

Absorbancy of the wool yarn (After applying 8 g AgNPs solution for 20 cm length)

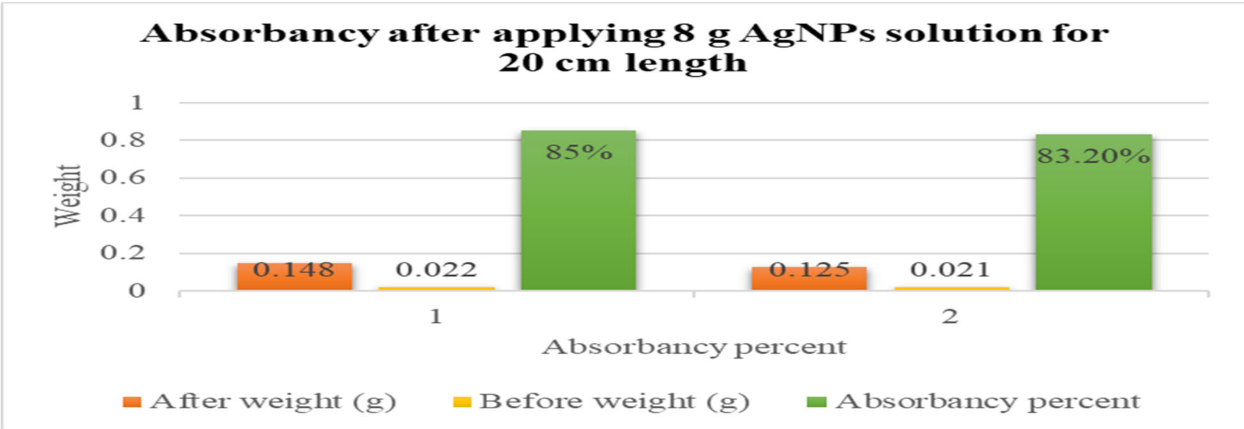


Figure 6. *Absorbancy of the wool yarn after applying conductive ink solution*

Figure 6 shows that the average solution take-up centage (absorbancy) of wool yarn after the application of conductive ink is 84.17% which is much higher than the avarage absorbency of other yarns. So the conductivity of the wool yarn will be higher than other yarns.

pH of the conductive ink solution

The measured pH of the conductive ink solution is 10.14.

Viscosity of the conductive ink solution

$\rho_{1=1.2988\ \mathrm{g/ml}}$

$t_{1=37\ \mathrm{s}}$

So, $\frac{\mu_1}{\mu_2} = \frac{\rho_1 t_1}{\rho_2 t_2} = \frac{\mu_1}{0.89} = \frac{1.2988\times37}{1\times18.2}$

So, μ_1= 2.35 cp

The printable conductive ink's viscosity should be low (1-15 cP) so that it can pass through the mesh fabric of the template easily and be attached with the substrates.

Electrical conductivity

The main purpose of this study is to measure the electrical conductivity of the different yarns or fabrics in different conditions. Results show the conductivity of wool yarn and silk fabrics in Figures 7 and 8.

Measurement of conductivity of wool yarn (σ after drying)

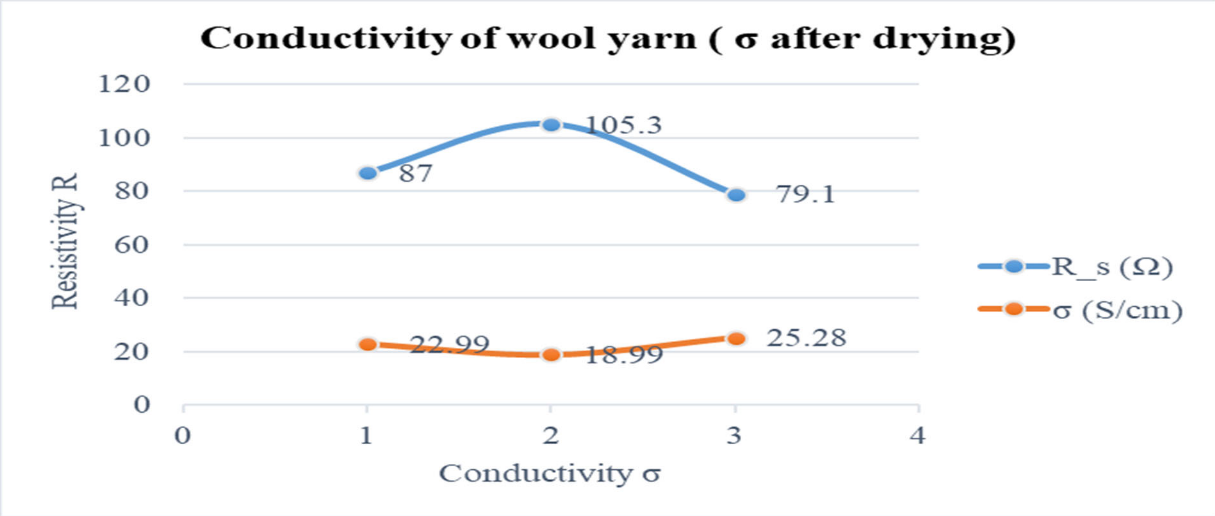


Figure 7. *The conductivity of the wool yarn.*

Measurement of conductivity of silk fabric (σ after drying)

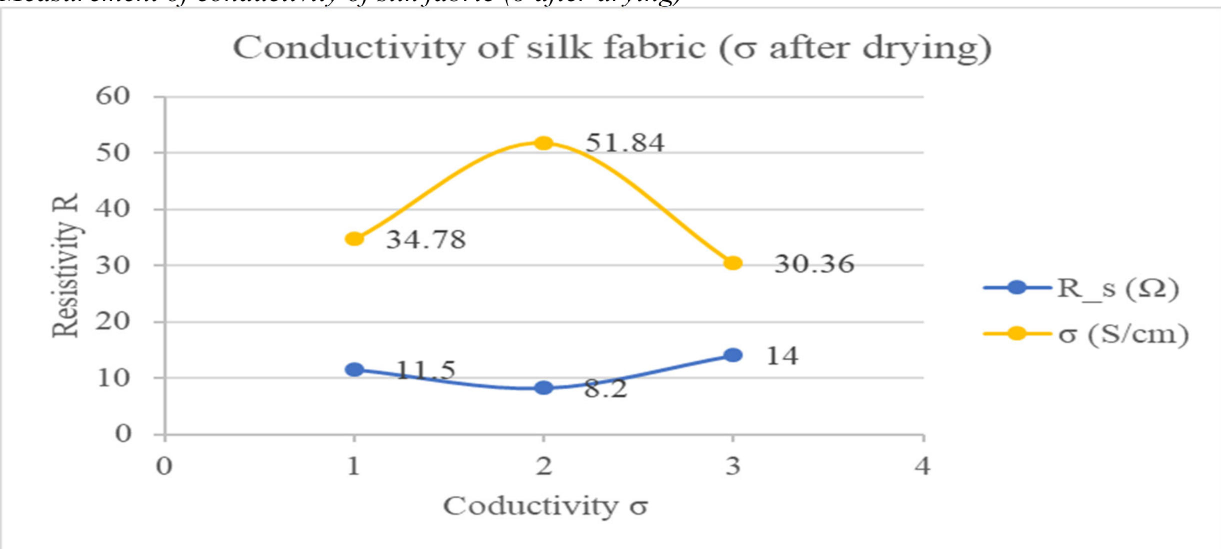


Figure 8. *The conductivity of the silk fabric.*

Figures 7 and 8 show that the conductivity of silk is higher than wool because normally silk fiber shows a poor conductor of electricity. İt forms a static charge when it is handled under different conditions. That's why silk fabric is more conductive in nature.

Colorfastness to rubbing (dry & wet)

For measuring the colorfastness to rubbing in both dry and wet conditions of the wool yarn and silk fabric crock meter is used.

Colorfastness to rubbing (dry)

The testing value of the wool yarn is 3 on the grayscale which fared well but the testing value of the silk fabric is 1/2 on the grayscale which is below standard means staining on the crock meter's fabric surface was heavy.

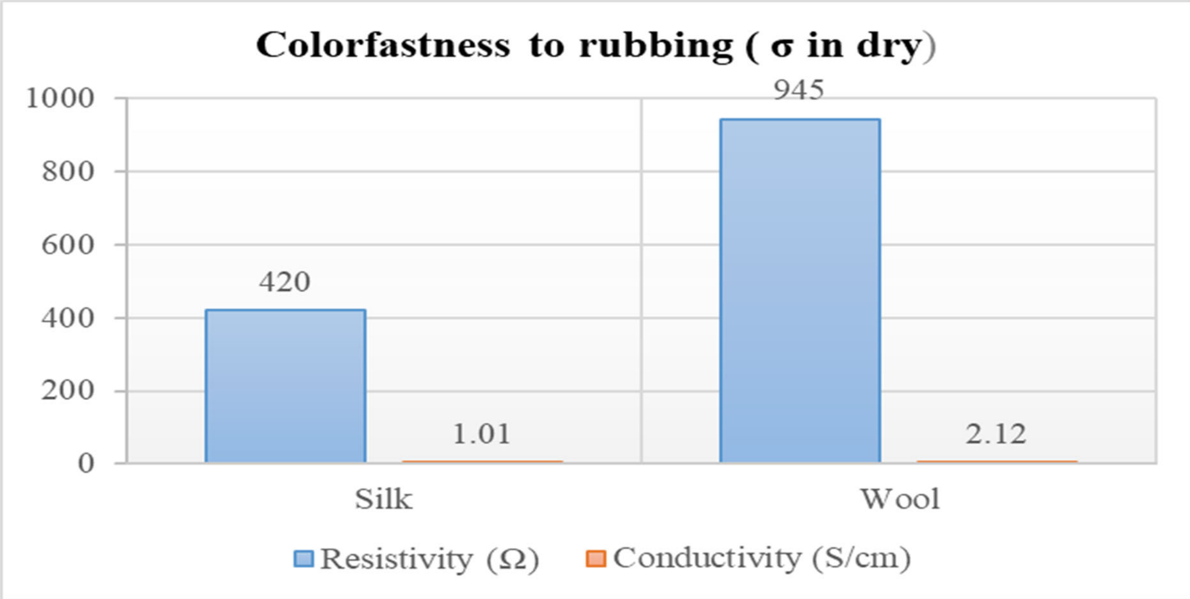


Figure 9. *The conductivity of silk fabric and wool yarn after color fastness to rubbing (dry).*

Colorfastness to rubbing (wet)

The testing value for both the wool yarn and the silk fabric is 1/2 and 1 on the grayscale which is below standard means staining on the crock meter's fabric surface was heavy.

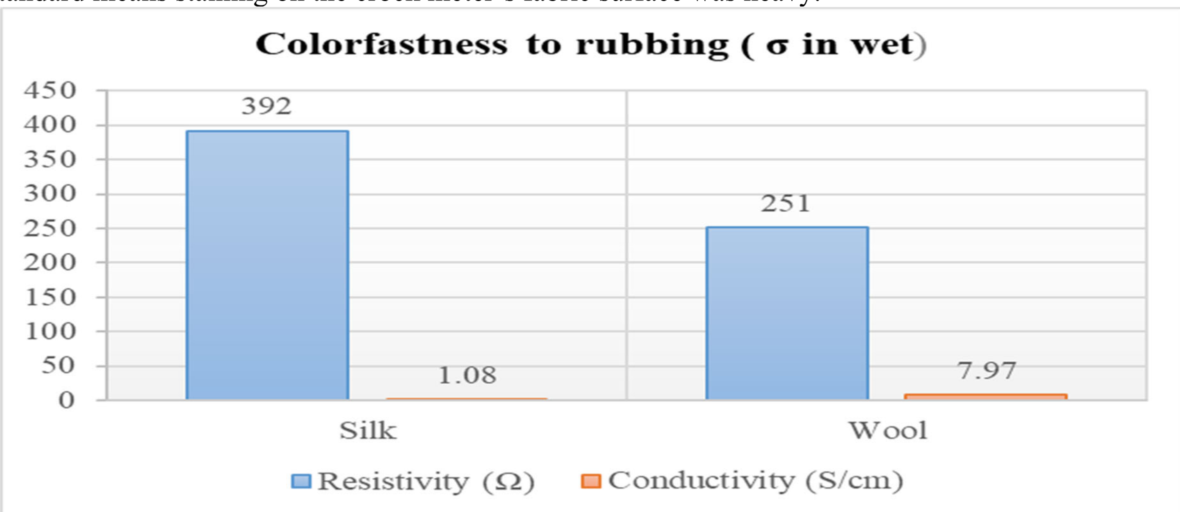


Figure 10. *The conductivity of silk fabric and wool yarn after color fastness to rubbing (wet).*

Figures 9 and 10 show that after the color-fastness to rubbing test (dry and wet), wool's conductivity is much higher than silk because the force applied during the test has increased the inter-molecular bond of wool yarn which also increase static electricity as well as conductivity. On the other hand, silk fabric does not create such kind of intermolecular bond. As a result, its conductivity remains unchanged.

Washing fastness (σ after drying)

A lab washing machine is used to wash the samples in appropriate conditions. Washing has been done to find out how many washes it can stand and remains its conductivity. The details result is shown in figure 11.

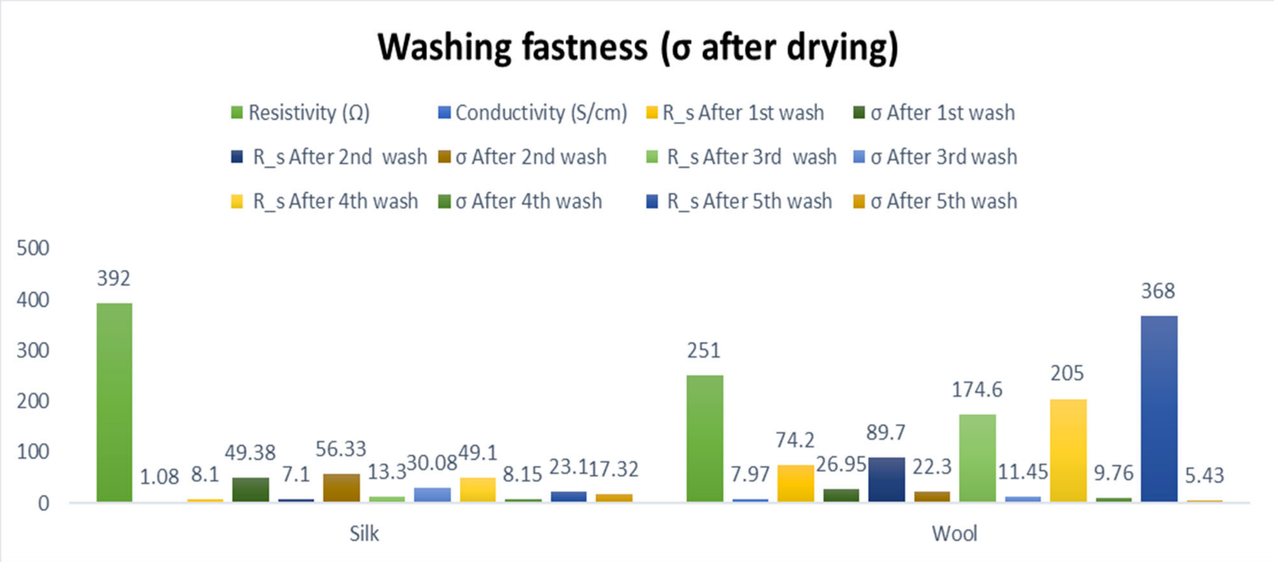


Figure 11. *The conductivity of silk fabric and wool yarn after washing (σ after drying).*

Figure 11 shows that after the wash fastness test, the conductivity of wool gradually decreases because of losing the inter-molecular bond during washing but its conductivity shows kind of stability. On the other hand, the conductivity of silk randomly changes may cause because of its static charge which may vary during different processes and different temperatures.

4. Conclusion

The dyeing method is much easier than any other method and economically sound. Results show that the conductivity of silk fabric is higher than wool yarn. But wool yarn's conductivity slowly decreases after washing as its higher absorbency of ink solution and uniform diameter contains its conductivity for a long time. On the other hand, the conductivity of silk fabric frequently changes because of its low absorbency and thinner surface. When silk fabric is washed, ink particles are also washed away with it because of the weak bond between particles and the fabric surface. So the stability and longevity of wool yarn are much higher than silk fabric found in this study.

References

[1] M.G. Adesse, C. Loghin, I. Dulgheriu, and E. Loghin, "Comfort Evaluation of Wearable Functional Textiles." Materials 14(21), p.6466, (2021).
[2] P. Xue, XI. Tao, MY. Leung, H. Zhang, "Electromechanical properties of conductive fibers, yarns, and fabrics." Wearable Electron. Photonics 81, 81-104, (2005).
[3] M. Stoppa, and A. Chiolerio. "Wearable electronics and smart textiles: A critical review." sensors 14, no. 7: 11957-11992 (2014).
[4] E. Dimitriou, and N.S. Michailidis. "Printable conductive inks used for the fabrication of electronics: An overview." Nanotechnology (2021).
[5] R.R. Bonaldi, "Electronics used in high-performance apparel—Part 1/2." In High-Performance Apparel, pp. 245-284. Woodhead Publishing, 2018.
[6] W. Hou, L. Qingwei, X. Shuang, S. Yujun, and Q. Lei, "Prospects and Challenges of Flexible Stretchable Electrodes for Electronics." Coatings 12, no. 5, 558 (2022).
[7] G.B Tseghai, B. Malengier, K.A. Fante, A.B. Nigusse, & L. Van Langenhove, "Integration of conductive materials with textile structures, an overview." Sensors, 20(23), 6910, (2020).
[8] M. Repon, and D. Mikučionienė, "Progress in Flexible Electronic Textile for Heating Application: A Critical Review". Materials, 14(21), p.6540, (2021).

[9] P. Anne Marie Helmenstine, «https://www.thoughtco.com,» 4, 6, 2022. [Online]. Available: https://www.thoughtco.com/the-most-conductive-element-606683.
[10] C. Marambio-Jones, and H. Eric, "A review of the antibacterial effects of silver nanomaterials and potential implications for human health and the environment." Journal of nanoparticle research 12, no. 5: 1531-1551, (2010).
[11] C. Fang, Z. Juanjuan, C. Xiqu, and G.J. Weng. "Calculating the electrical conductivity of graphene nanoplatelet polymer composites by a Monte Carlo method." Nanomaterials 10, no. 6 (2020): 1129, (2020).
[12] L. Chen, P. Hu, L. Zhang, S. Huang, L. Luo, and C. Huang, "Toxicity of graphene oxide and multi-walled carbon nanotubes against human cells and zebrafish." Science China Chemistry 55, no. 10: 2209-2216, (2012).
[13] I.A Kariper, "Conductive Ink Next Generation Materials: Silver Nanoparticle/Polyvinyl Alcohol/Polyaniline." Journal of Inorganic and Organometallic Polymers and Materials: 1-10, (2022).
[14] D.C. Trinh, T.M.D. Dang, K.H. Tran, and M.C. Dang, "Preparation of conductive ink based on silver nanoparticles." Advances in Natural Sciences: Nanoscience and Nanotechnology 10, no. 4: 045007, (2019).
[15] G.B Tseghai, B. Malengier, K.A. Fante, A.B. Nigusse, & L. Van Langenhove, "PEDOT: PSS-based conductive textiles and their applications." Sensors 20, no. 7: 1881, (2020).
[16] W. Dang, "Stretchable interconnects for smart integration of sensors in wearable and robotic applications." PhD diss., University of Glasgow, 2018.
[17]«global.ihs,»[Online].Available:https://global.ihs.com/doc_detail.cfm?document_name=AATCC%2020A&item_s_key=00264363. [Accessed: 5 6 2022].
[18] «scribd,» [Online]. Available: https://www.scribd.com/document/341830139/Textile-Testing. [Accessed: 5 6 2020].
[19] «astm,» [Online]. Available: https://www.astm.org/d3776_d3776m-09ar17.html. [Accessed: 4 6 2022].
[20] «members.aatcc,» [Online]. Available: https://members.aatcc.org/store/tm197/617/. [Accessed: 5 6 2022].
[21] «ipstesting,» [Online]. Available: https://ipstesting.com/find-a-test/aatcc-test-method/aatcc-8-colorfastness-to-crocking/. [Accessed: 5 6 2022].
[22]«global.ihs,»[Online].Available:https://global.ihs.com/doc_detail.cfm?document_name=AATCC%206&item_s_key=00264343. [Accessed: 5 6 2022].
[23] M.R. Cannon, and M. R. Fenske, "Viscosity measurement." Industrial & Engineering Chemistry Analytical Edition 10, no. 6: 297-301, (1938).
[24] Y.E. Elmogahzy, "Performance characteristics of technical textiles: Part I: E-textiles." Engineering Textiles: 347-364, (2020).
[25] S. Mandal, S. Gaan, M. Camenzind, S. Annaheim, and R.M. Rossi, "Thermal characterization of fire-protective fabrics." In Thermal Analysis of Textiles and Fibers, pp. 355-387. Woodhead Publishing, 2020.
[26] M.R. Miah, F.Y. Telegin, M.S. Miah, M.A. Shahid, M.S. Rahman, and J. Ran, "Comparative analysis of colour strength and fastness properties on extracts natural dye from onion's outer shell and its use in eco-friendly dyeing of silk fabric." International journal of photochemistry and photobiology 2, no. 1: 1-8, (2017).